Residual Circulation and Tropopause Structure

submitted to JAS

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What is the effect of the (stratospheric) residual circulation on lower stratospheric static stability and tropopause structure?

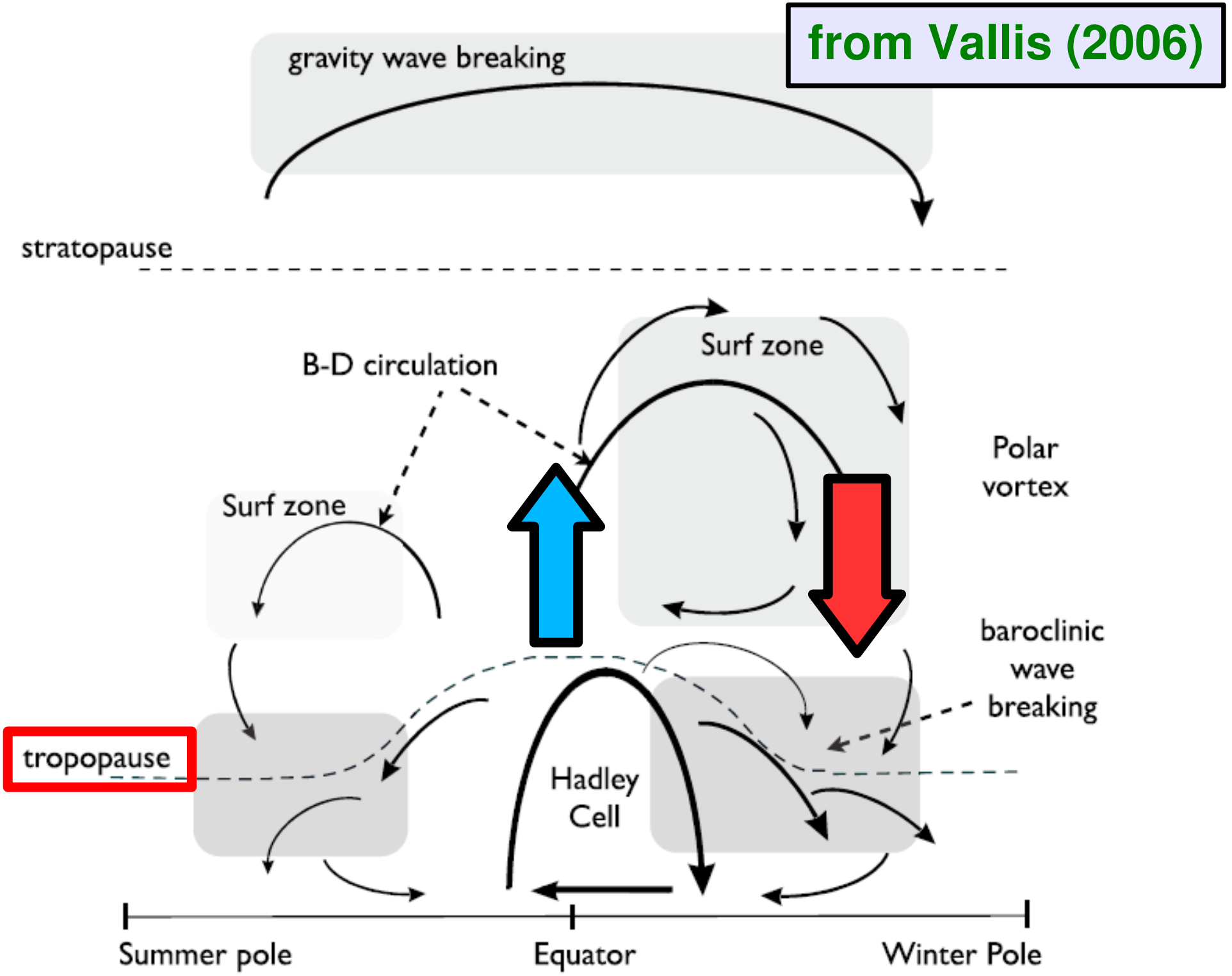
Background

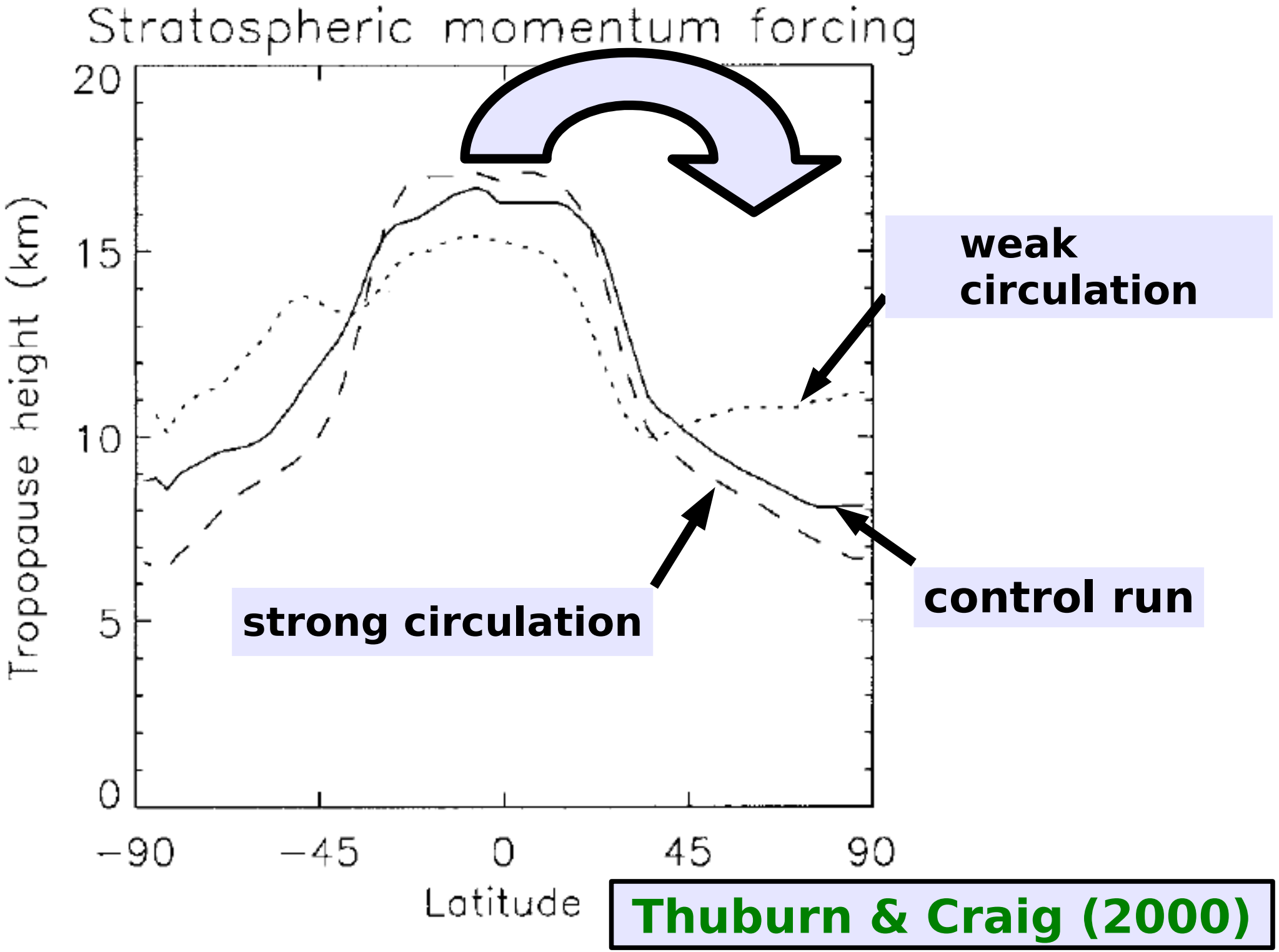
- Stratospheric residual (~ Brewer-Dobson) circulation tends to: lift tropical tropopause and lower extratropical tropopause

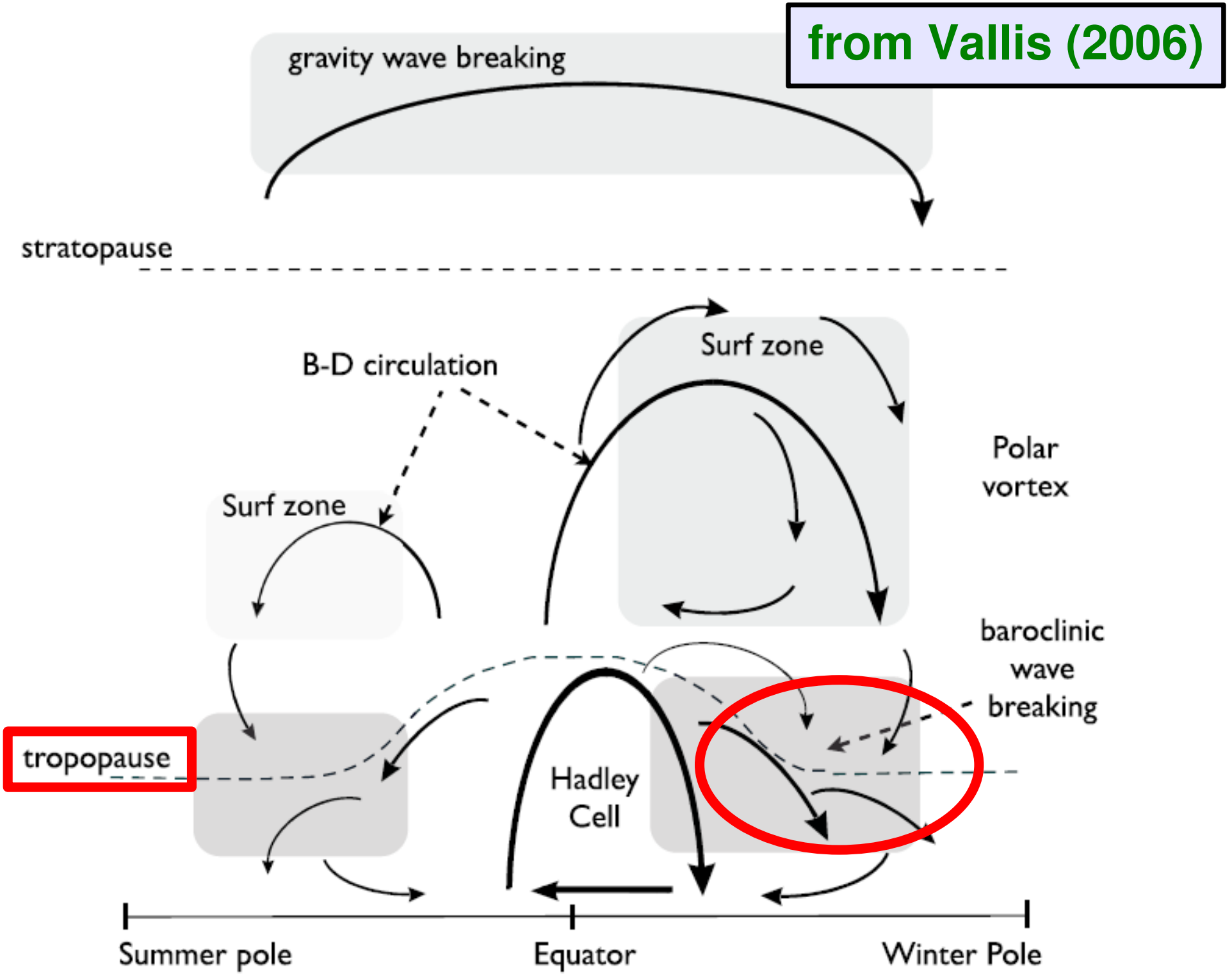
  → By how much?

- Lower stratospheric static stability exhibits characteristic vertical structure (~ tropopause inversion layer, TIL)

  → To what extent is this structure related to the residual circulation?


from Vallis (2006)
gravity wave breaking
stratopause
B-D circulation
Surf zone
Surf zone
Polar
vortex
baroclinic
wave
breaking
tropopause
Hadley
Cell
Summer pole
Equator
Winter Pole


Stratospheric momentum forcing
20
15
10
5
0
Tropopause height (km)
−90
−45
0
45
90
Latitude
weak circulation
strong circulation
control run
Thuburn & Craig (2000)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gravity wave breaking
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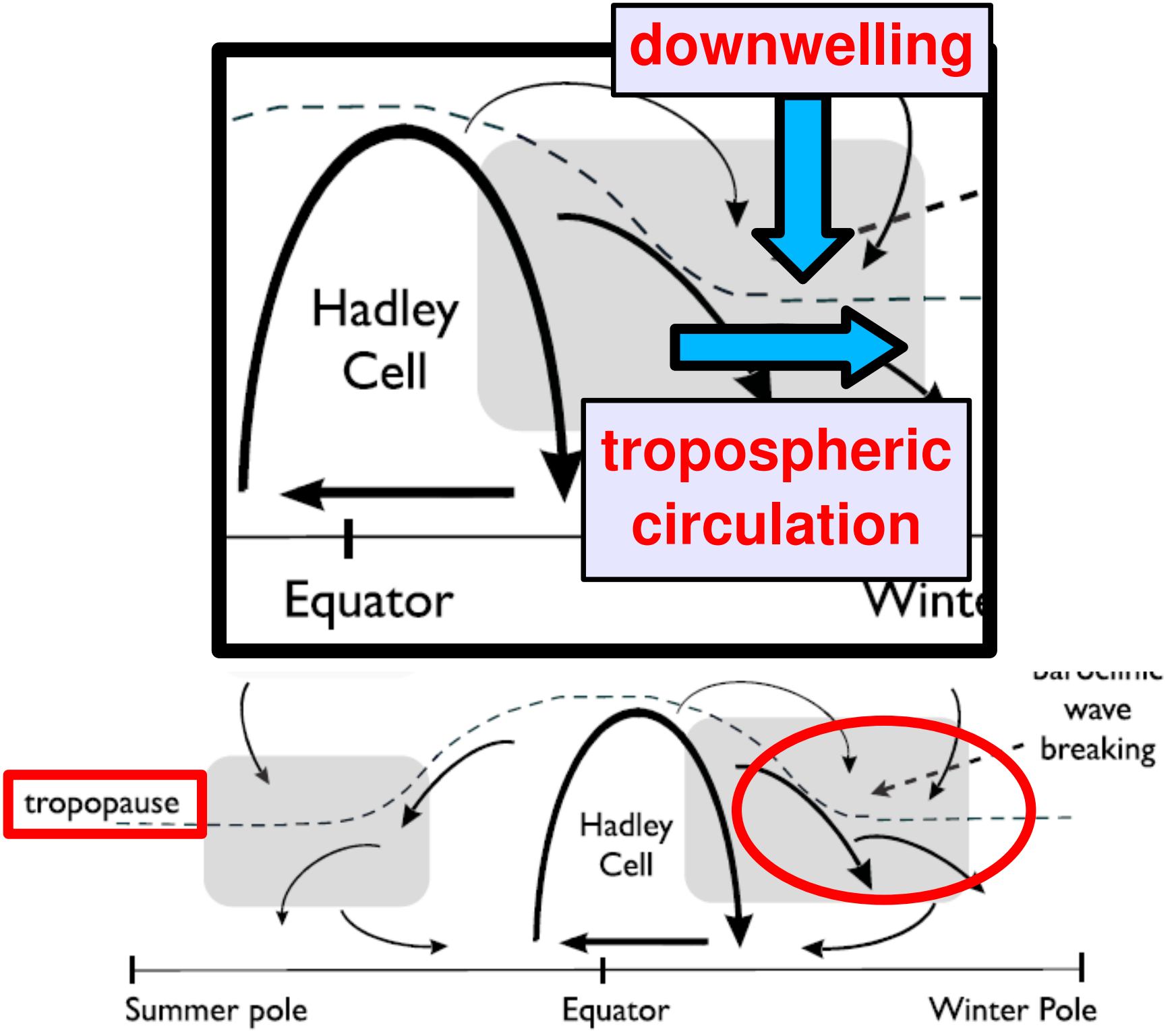
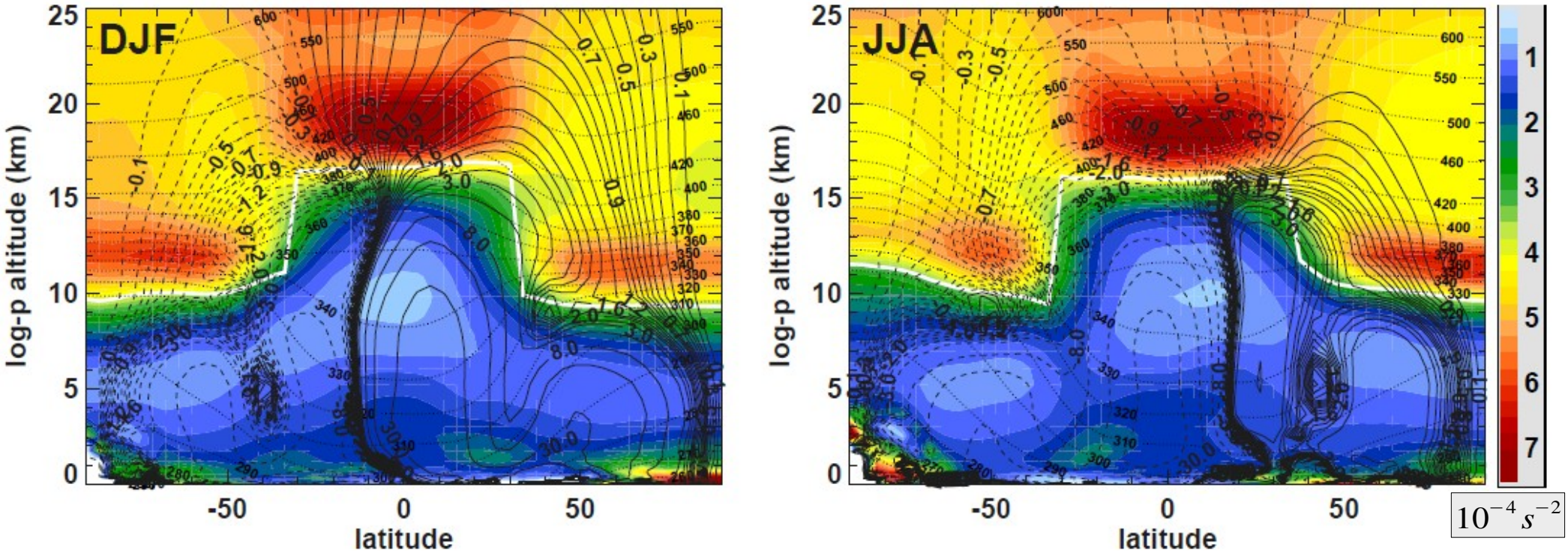

downwelling
Hadley Cell
tropospheric circulation
Equator
Winte
wave breaking
tropopause
Hadley Cell
Summer pole
Equator
Winter Pole

Tools

- Canadian Middle Atmosphere Model (CMAM): comprehensive CCM, T47L71, i.e. vertical resolution near tropopause ~ 1 km
- ERA40 on model levels (T159L60), vertical resolution similar to CMAM near tropopause
- Only CMAM results will be shown here, but all results are consistent between CMAM and ERA40.
- Column Radiation Model (CRM): stand-alone radiative transfer code out of NCAR CCM3.

Static Stability (N^2) & Residual Stream-function (seasonal zonal means)



→ enhanced N^2 just above the (global) tropopause – tropopause inversion layer (TIL)

→ note vertical structure of residual circulation near the tropopause

Transformed Eulerian (~ Residual) Mean Thermodynamic Equation

$$\partial_t \overline{\Theta} + \overline{w}^* \partial_z \overline{\Theta} + \overline{v}^* \partial_y \overline{\Theta} \approx \overline{Q}$$

Residual Vertical & Meridional Velocities

Diabatic Heating (mainly radiative in the stratosphere)

form equation for $\overline{N^2} = g\overline{\Theta}^{-1}\partial_z\overline{\Theta}$:

$$\partial_t \overline{N^2} \approx -\partial_z(\overline{w}^* \overline{N^2}) - g\partial_z(\overline{v}^* \overline{\Theta}^{-1} \partial_y \overline{\Theta}) + g\partial_z(\overline{\Theta}^{-1} Q)$$

Vertical structures of both, w^* and N^2 are important!

usually small

Forcing due to Residual Circulation

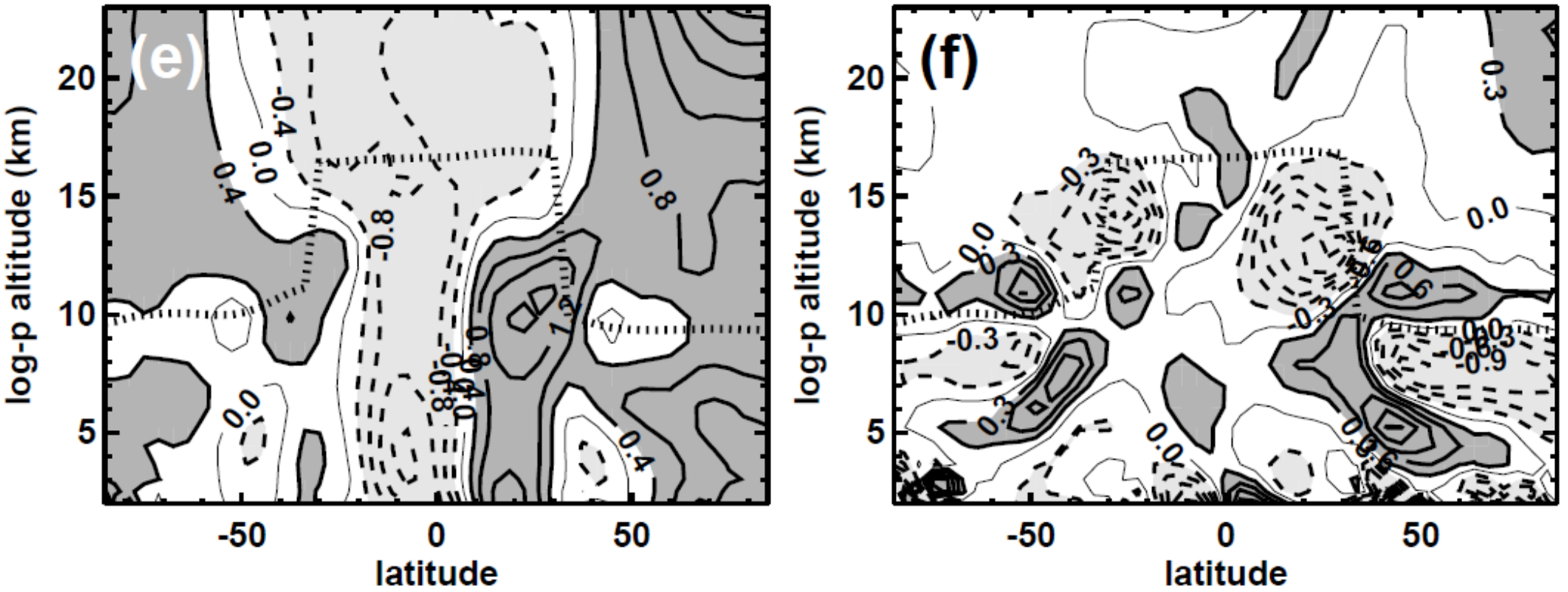
Θ – Heating Rates (K/day)

$$-\overline{v}^*\partial_y\overline{\Theta} - \overline{w}^*\partial_z\overline{\Theta}$$

DJF

Static Stability Forcing ($10^{-5}s^{-2}$/day)

$$-\partial_z(\overline{w}^*\overline{N^2}) - g\partial_z(\overline{v}^*\overline{\Theta}^{-1}\partial_y\overline{\Theta})$$

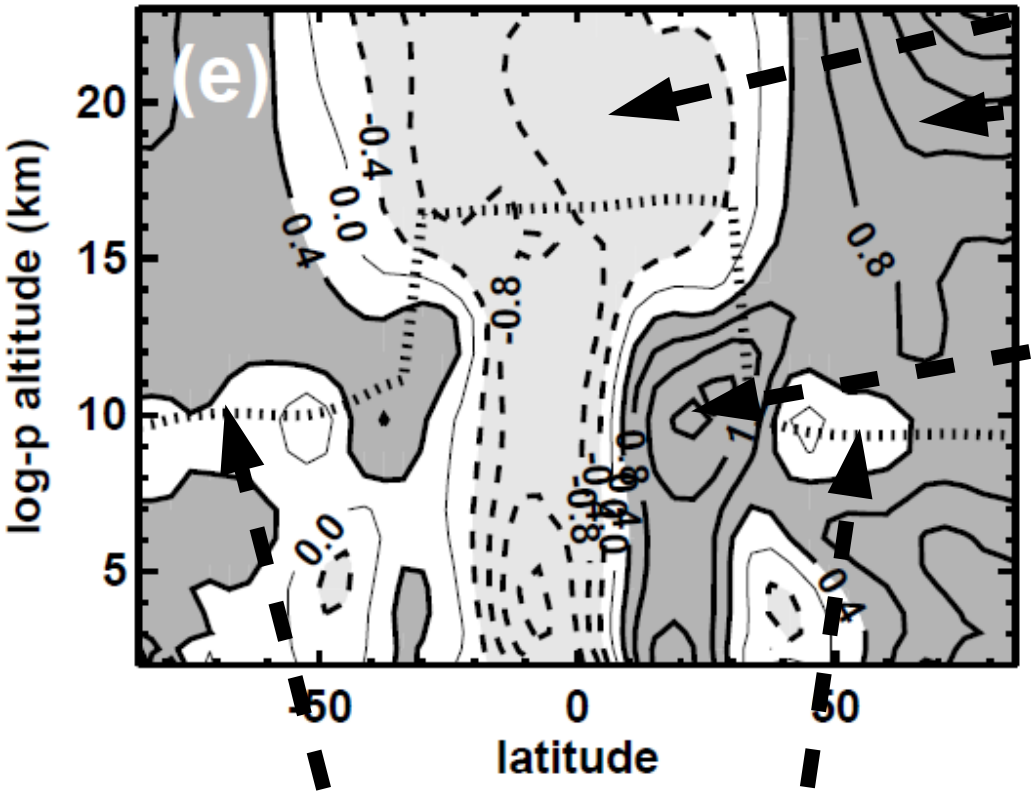


- dark/light shading: values above/below ±0.4 K/day (left), above/below ±0.3·$10^{-5}s^{-2}$/day (right)
- dominant contribution (with few exceptions) comes from vertical residual velocity contribution

Forcing due to Residual Circulation

Θ – Heating Rates (K/day), DJF

$$-\overline{v}^*\partial_y\overline{\Theta} - \overline{w}^*\partial_z\overline{\Theta}$$



Tropical Upwelling

Extratropical Downwelling

Localized subtropical upper tropospheric warming maximum

↳ double tropopause formation?

Note vertical structure near tropopause!

(slight) cooling @ subtropical edges of tropical TP is due to meridional contribution!

Forcing due to Residual Circulation

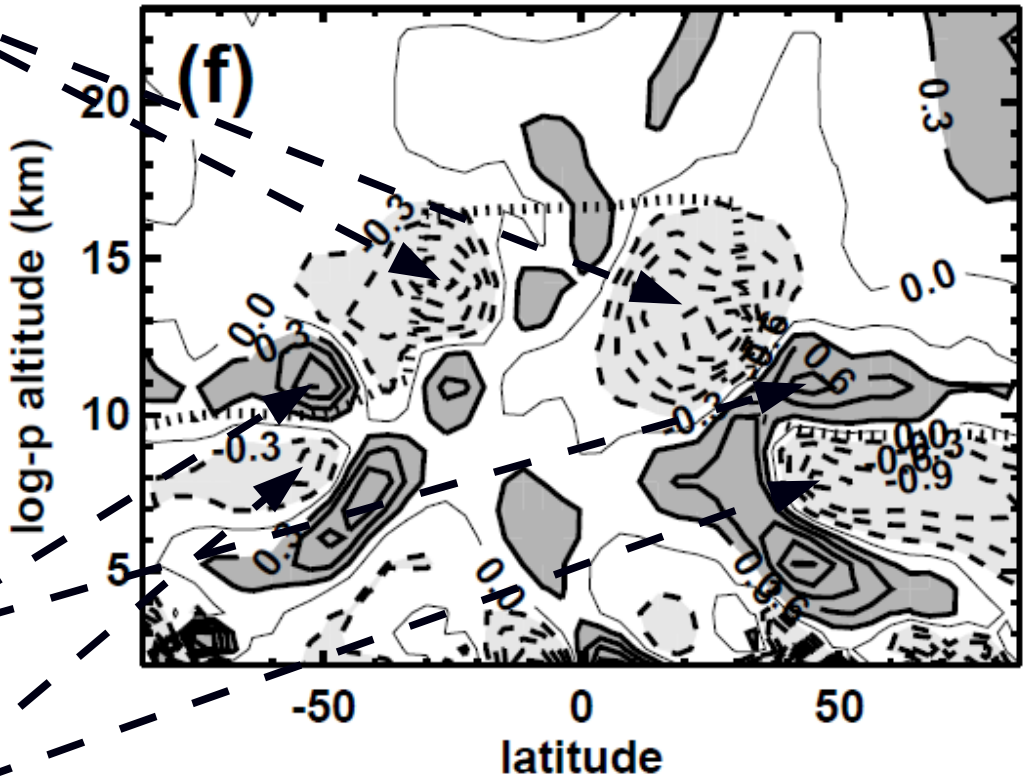
$$-\partial_z(\overline{w}^*\overline{N^2}) - g\partial_z(\overline{v}^*\overline{\Theta}^{-1}\partial_y\overline{\Theta})$$

Static Stability Forcing ($10^{-5}s^{-2}$/day), DJF

Large negative forcing in subtropical uppermost troposphere

(combined effect of vertical and meridional contribution)

↳ double tropopause formation?



Dipole structure of positive forcing just above TP (due to $\overline{w}^*$) and negative forcing just below TP (due to $\overline{v}^*$)

pronounced forcing structure everywhere around the tropopause

Stratospheric Radiative Equilibrium (SRE) Solutions:

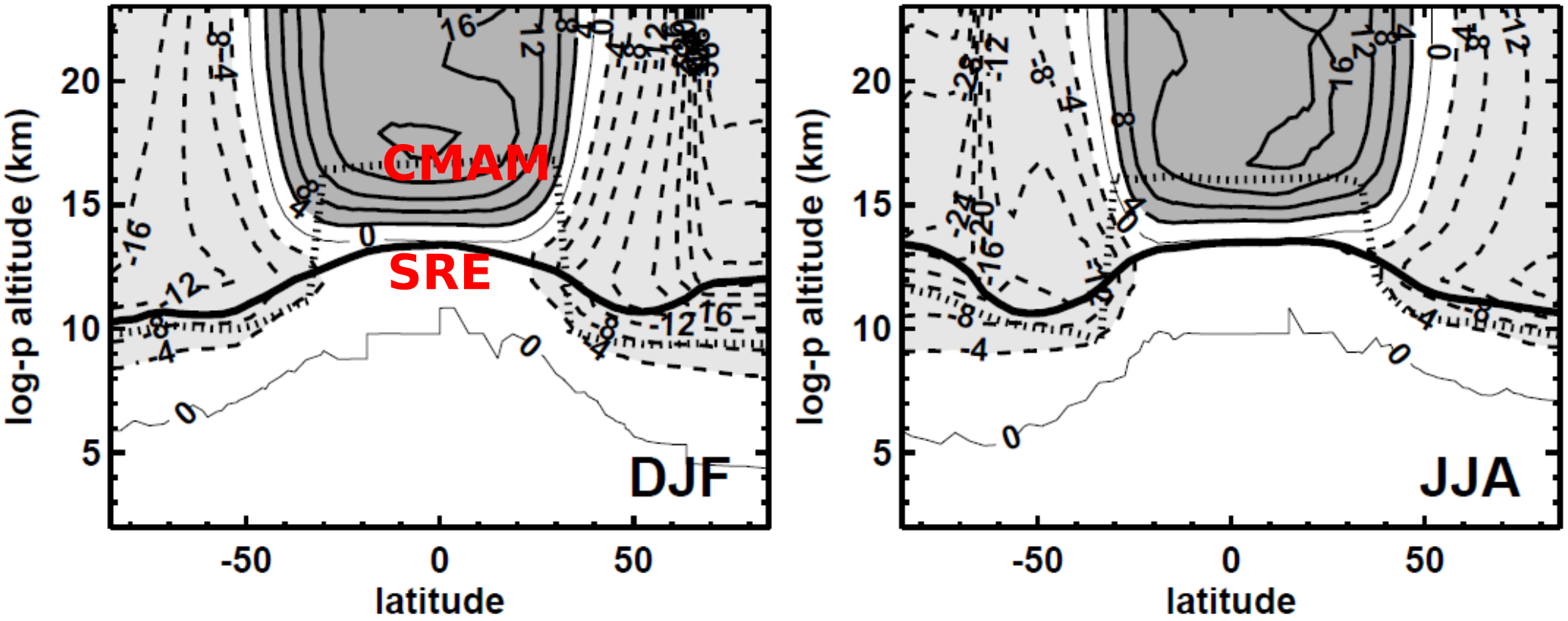
- constrain tropospheric climate to the one simulated by CMAM
- perform off-line radiative transfer calculations (clear-sky, using CRM) to obtain stratospheric temperatures in radiative equilibrium given CMAM's tracer distribution

Stratospheric Circulation-Radiation (SCR) Solutions:

- add circulation-induced heating rates to above radiative calculations

How do the resulting tropopause height and lower stratospheric static stability compare to CMAM?

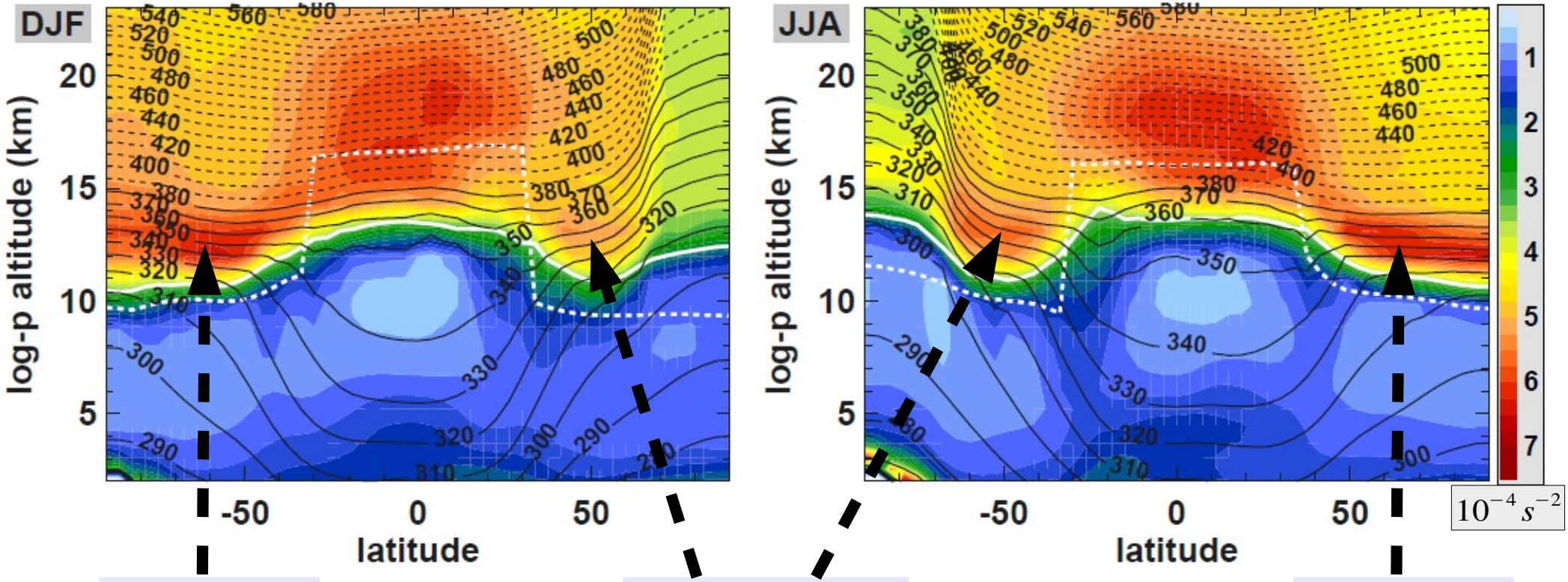
Stratospheric Radiative Equilibrium Temperature Perturbation $T_{rad} - T_{CMAM}$



→ expected warm/cold dipole structure between tropics and extratropics

→ much lower tropical tropopause in SRE (~3–4 km), somewhat higher extratropical tropopause (~1–2 km)

Stratospheric Radiative Equilibrium Static Stability (N^2) Structure



Summer TIL!

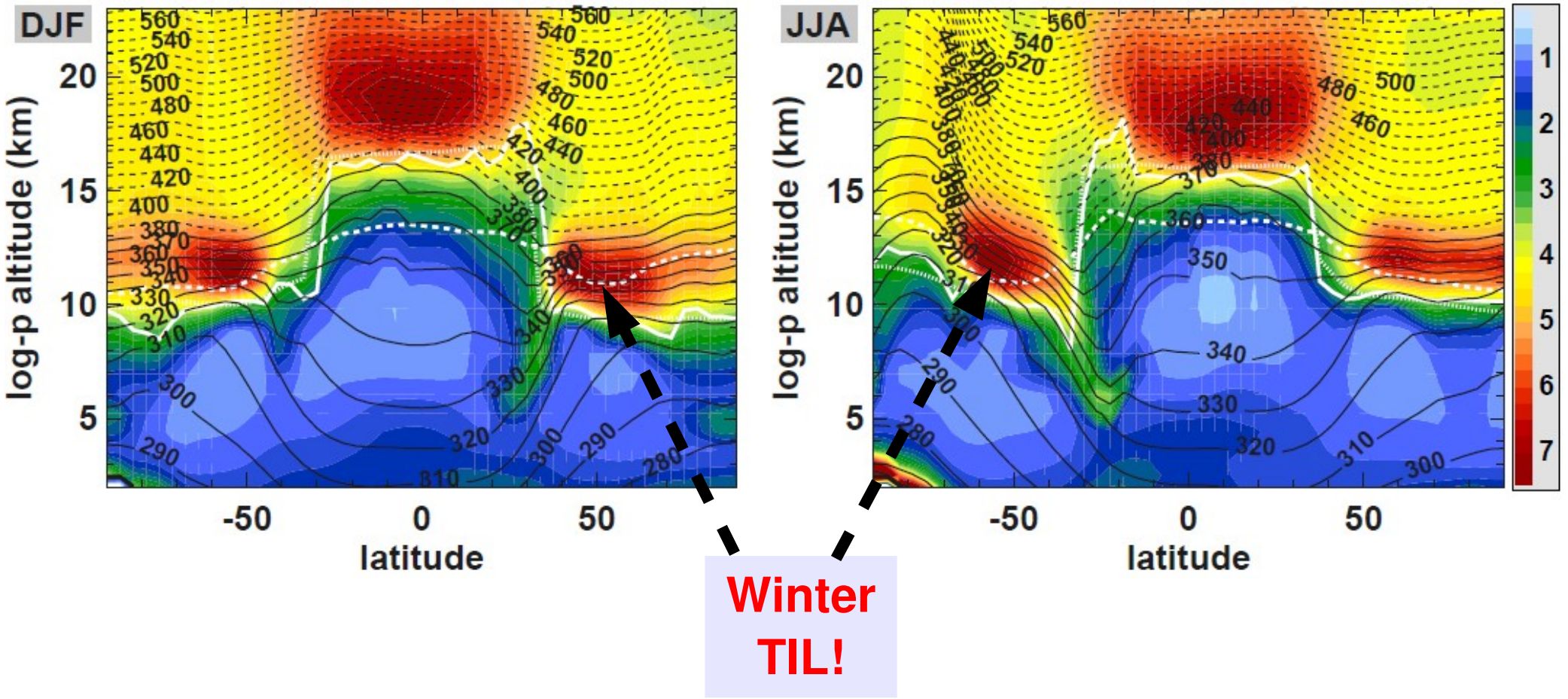
Hardly any winter TIL!

Summer TIL!

→ note strongly reduced N^2 in winter polar regions due to polar night (no strat. dynamical heating)

→ tropical TIL weakened compared to CMAM

Circulation–Radiation Solution Static Stability (N^2) Structure

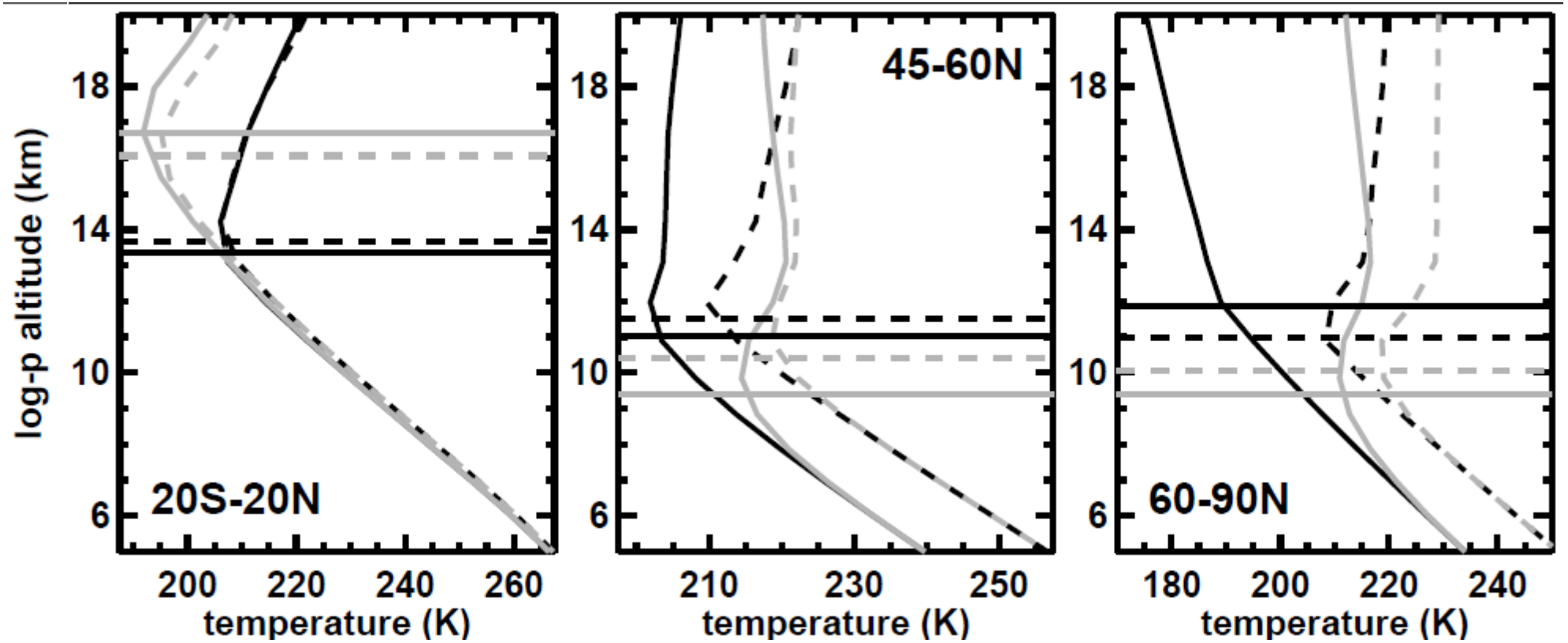


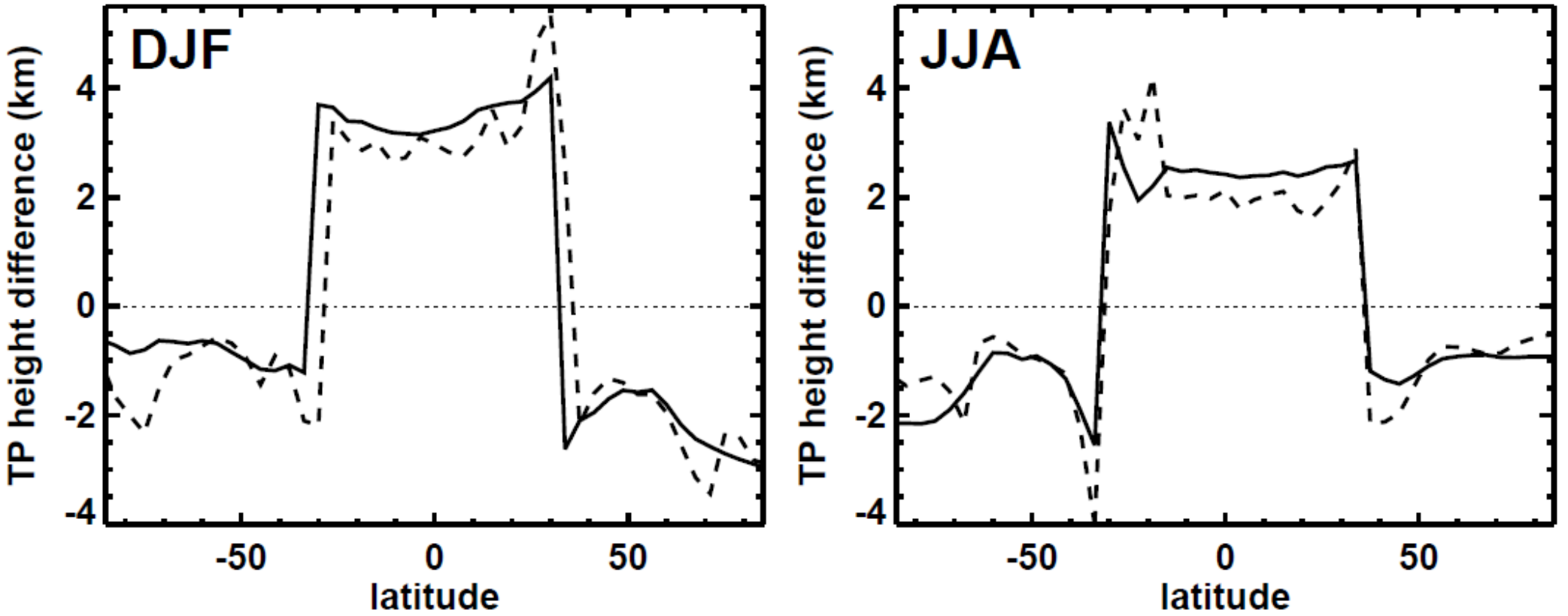
→ note good agreement between circulation-radiation tropopause (dotted) and CMAM's tropopause (full)

→ much stronger tropical TIL than in SRE solution

Conclusions

- Stratospheric residual (Brewer-Dobson) circulation strongly enhances equator-to-pole contrast in tropopause height (by ~ factor of 2 compared to a stratosphere in radiative equilibrium)
- Dipole structure of strongly positive (negative) static stability forcing just above (below) the mid-latitudinal tropopause in winter effectively sharpens tropopause and appears to cause TIL there
- Forcing structure in subtropical upper troposphere should favor formation of double tropopauses


log-p altitude (km)
18
14
10
6
20S-20N
200
220
240
260
temperature (K)
45-60N
210
230
250
60-90N
180
200
220
240


DJF
JJA
TP height difference (km)
latitude
4
2
0
-2
-4
-50
0
50